Possible Surprises and New Physics

- Neutrino Preliminaries
- Anomalies, alternatives, perturbations
- Alternatives to the Seesaw
- Sterile neutrinos
- Far out possibilities
- What if MiniBooNE sees a positive signal?
- Relic neutrinos

Occam's Razor

through the ages...

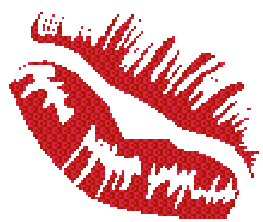
Pluralitas non est ponenda sine necessitate.

(Plurality should not be posited without necessity.)

\- William of Ockham

Everything should be made as simple as possible, but not simpler.

\- Albert Einstein



Keep

It

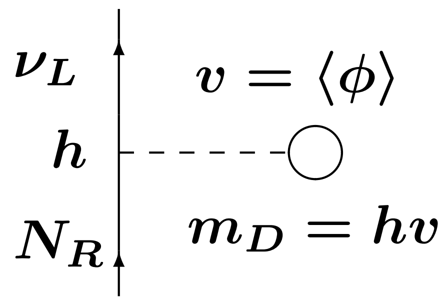
Simple,

Stupid !

Neutrino Preliminaries

- **Weyl fermion**
  - Minimal (two-component) fermionic degree of freedom
  - $\psi_L \leftrightarrow \psi_R^c$ by CPT
- **Active Neutrino (a.k.a. ordinary, doublet)**
  - in $SU(2)$ doublet with charged lepton $\longrightarrow$ normal weak interactions
  - $\nu_L \leftrightarrow \nu_R^c$ by CPT
- **Sterile Neutrino (a.k.a. singlet, right-handed)**
  - $SU(2)$ singlet; no interactions except by mixing, Higgs, or BSM
  - $N_R \leftrightarrow N_L^c$ by CPT
  - Almost always present: Are they light? Do they mix?

- **Dirac Mass**
  - Connects distinct Weyl spinors (usually active to sterile): $(m_D \bar{\nu}_L N_R + h.c.)$
  - 4 components, $\Delta L = 0$
  - $\Delta I = \frac{1}{2} \rightarrow$ Higgs doublet
  - Why small? LED? HDO?



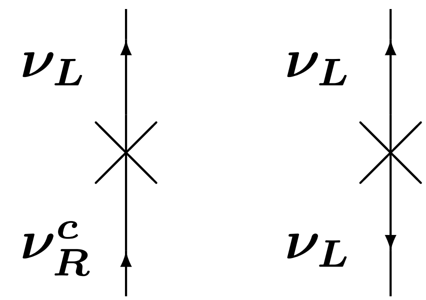
- **Majorana Mass**

  – Connects Weyl spinor with itself:
  $\frac{1}{2}(m_T \bar{\nu}_L \nu_R^c + h.c.)$ (active);
  $\frac{1}{2}(m_S \bar{N}_L^c N_R + h.c.)$ (sterile)

  – 2 components, $\Delta L = \pm 2$

  – Active: $\Delta I = 1 \rightarrow$ triplet or seesaw

  – Sterile: $\Delta I = 0 \rightarrow$ singlet or bare mass



- **Mixed Masses**

  – Majorana and Dirac mass terms

  – Seesaw for $m_S \gg m_D$

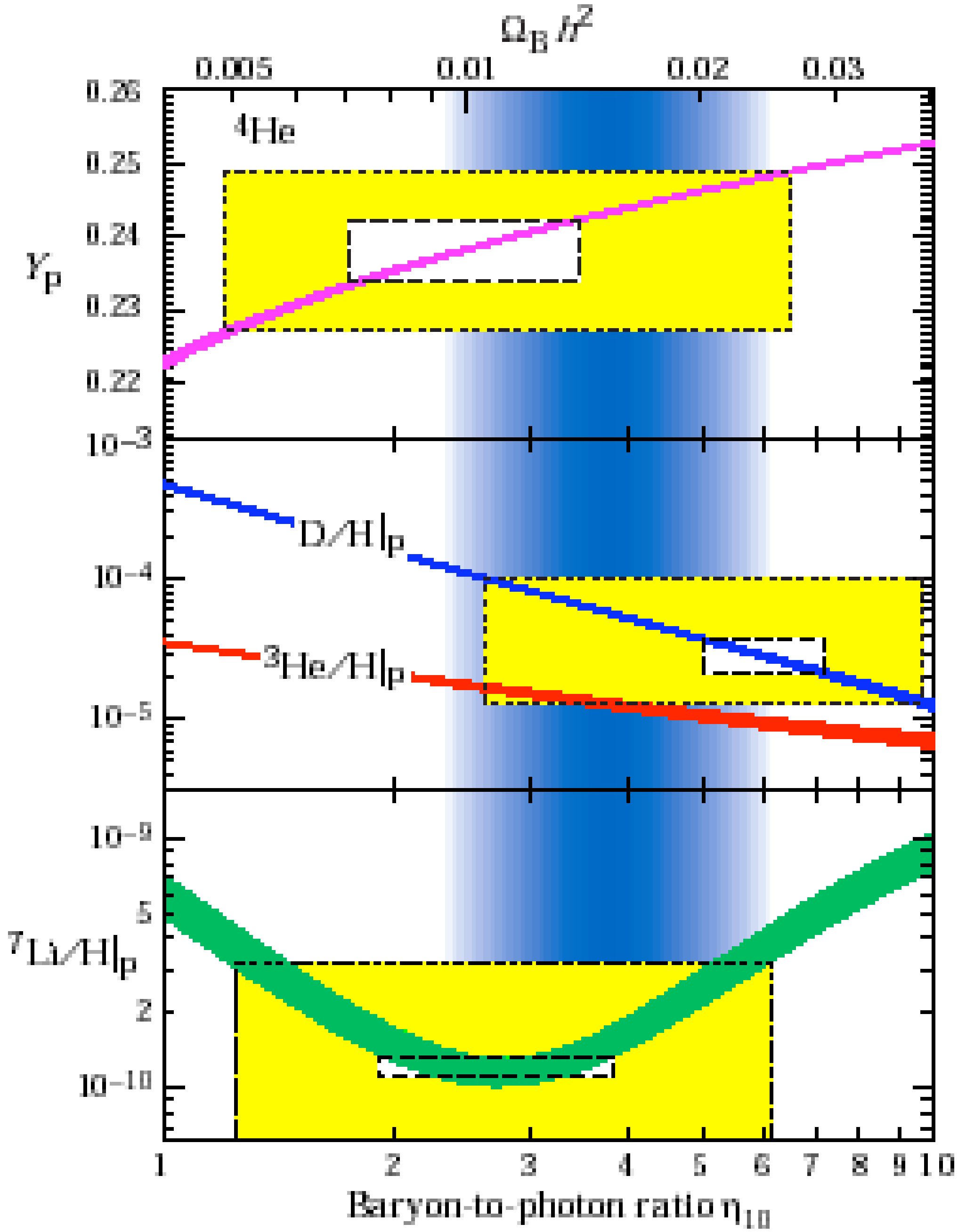
  – Ordinary-sterile mixing for m_S and m_D both small and comparable (or $m_S \ll m_d$ (pseudo-Dirac))

Anomalies, alternatives, perturbations

- **Anomalies/indications for new physics**
  - LSND
  - NuTeV ($\sin^2\theta_W = 0.2277(16)$ is 3σ high)
    (Anomalous ν couplings? Z'? QCD effect?)
  - Invisible Z width ($N_\nu = 2.983(9)$ is 1.9σ low)
    (Fluctuation? Anomalous couplings?)
  - Neutrinoless double beta decay?
  - High energy cosmic rays beyond GZK cutoff
    (New physics?, Z-bursts? Energy calibration uncertainties?)

– **Big Bang Nucleosynthesis (BBN)**

  * n_B/n_γ **from** D **abundance agrees with CMB.** ^4He **abundance is rather high for** $N_\nu = 3$**)**
    (Systematics? Large ν **degeneracy?)**
  * **Many effects (e.g., Dirac with new interactions, sterile neutrinos) predict even more** ^4He


$\Omega_B h^2$
0.005
0.01
0.02
0.03
^{4}He
Y_p
0.26
0.25
0.24
0.23
0.22
10^{-3}
D/H|p
10^{-4}
^{3}He/H|p
10^{-5}
10^{-9}
5
^{7}Li/H|p
2
10^{-10}
1
2
3
4
5
6
7
8
9
10
Baryon-to-photon ratio η_{10}

- Many ideas once considered alternatives to oscillations amongst the 3 active neutrinos

  - Atmospheric neutrinos: many alternatives could describe the (lower energy) contained events, but most excluded by (higher energy) upward throughgoing.
    (Often depend on LE or L rather than L/E.)

  - Solar (before KamLAND): several alternatives to LMA

  - Solar (after KamLAND): LMA established

- Can still consider new physics mechanisms as perturbations on dominant 3-flavor oscillations.

Alternatives to the GUT Seesaw

- **Elegant mechanism for small Majorana masses**
- **Leptogenesis**
- **Expect small mixings in simplest versions (can evade by lopsided e/d, Majorana textures, etc.)**
- **Large Majorana often forbidden, e.g., by extra $U(1)$'s**
- **Direct Majorana masses and large scales forbidden in some string constructions**
- **GUTs, adjoint Higgs, large Higgs hard to accomodate in simplest heterotic constructions**
- **LSND: active-sterile difficult in simple versions**

- Therefore, explore alternatives, e.g., with small Dirac and/or Majorana masses
  - Small Majorana from loops, R_p violation, or TeV seesaw
  - Small Dirac from large extra dimension or by higher dimensional operators, e.g., in intermediate scale models (e.g. $U(1)'$)

$$L_\nu \sim \left(\frac{S}{M_{Pl}}\right)^p L N_L^c H_2, \quad \langle S \rangle \ll M_{Pl}$$

$$\Rightarrow m_\nu \sim \left(\frac{\langle S \rangle}{M_{Pl}}\right)^p \langle H_2 \rangle$$

(flexible seesaw alternative; can also yield large ordinary-sterile mixing)

- **BBN constraints on Dirac neutrinos**
  - **Mass effects unimportant unless $m_\nu \gtrsim 10$ KeV**
  - **New interactions (e.g., TeV scale Z') allow $f\bar{f} \rightarrow \nu_R \bar{\nu}_R$ by Z' or $Z - Z'$ mixing; strongly constrained unless near decoupling (natural flat directions?)**

- Leptogenesis
  - Promising scenario for baryogenesis
  - Out of equilibrium decays of

$$N_{heavy} \rightarrow l + \text{ Higgs } \neq N_{heavy} \rightarrow \bar{l} + \text{ Higgs}$$

    created a *lepton* asymmetry
  - Electroweak tunneling (actually thermal fluctucation) then converts some of the lepton asymmetry into a baryon asymmetry!
  - Difficulties in supersymmetric version: gravitino problem suggests reheating temperature too low (unless N_{heavy} produced nonthermally or light gravitino)
  - Electroweak baryogenesis may be viable alternative
    * Small parameter space for MSSM (small Higgs, stop masses)
    * Adequate asymmetry for $U(1)'$ model

Sterile neutrinos

- **Motivations** (not all for same mass range)
  - LSND (need 4 mass eigenstates for LSND, Solar, atmospheric)
  - Improve LMA fit: Homestake rate low, no low energy turnup
  - r-process nucleosynthesis
- **Theoretical difficulties**
  - Almost all ν mass models involve sterile neutrinos, *but*
  - Are they light? (Not in seesaw)
  - Do active and sterile neutrinos mix?
    (Not for Dirac or pure Majorana)

- Need small/comparable Dirac and Majorana (or active-singlet, singlet-singlet) masses without canonical seesaw or SUSY protection of low scale
- Intermediate scale models? Large extra dimensions? Mirror worlds?

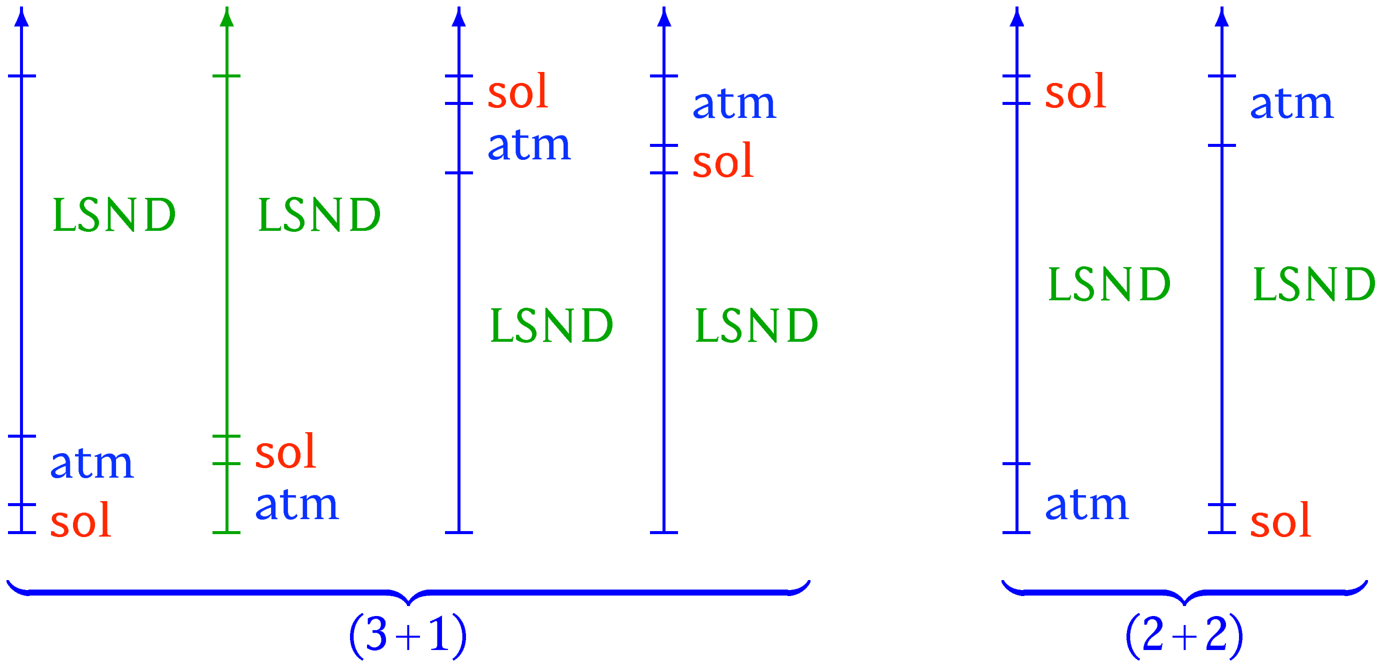


Figure 1: The six four-neutrino mass spectra, divided into the classes (3+1) and (2+2).

- Models and spectra
  - 2-2 models give very poor fit to Solar/atmospheric (Extra parameters?)
  - 3-1 probably excluded by reactor and accelerator disappearance
  - 3-2 give better fit, e.g., $\Delta m^2_{41} \sim 1$ eV^2, $\Delta m^2_{51} \sim 20$ eV^2
  - Would lead to rich oscillation physics
- BBN (and large scale structure) constraints
  - Hard to avoid thermalizing the sterile neutrino(s)
  - Can delay thermalization for large ($O(0.01 - 0.1)$) neutrino asymmetry
  - Problem aggravated in 3-2 schemes, but no detailed analysis

Far out possibilities

- Large extra dimensions, KK towers
- Mixing with heavy neutrinos (including nonorthogonal)
- Magnetic moments (SP, RSFP, RSFP + oscillations)
- Neutrino decay
- Decoherence, e.g. from large ν background
  (Tends to equilibrate flavors. Dominant unlikely)
- Equivalence Principle (VEP), Lorentz Invariance (LIV)
  (LE, excluded as dominant)
- CPT violation

- **New interactions**
- **Neutrino-antineutrino oscillations**
- **Large neutrino degeneracies**

Large extra dimensions, KK towers

- Fundamental scale $M_F \sim 1 - 100 \text{ TeV} \ll \bar{M}_{Pl} = 1/\sqrt{8\pi G_N} \sim 2.4 \times 10^{18}$ GeV

  Assume δ extra dimensions with volume $V_\delta \gg M_F^{-\delta}$

$$\bar{M}_{Pl}^2 = M_F^{2+\delta} V_\delta \gg M_F^2$$

  (Introduces new hierarchy problem)

  Black holes, graviton emission at colliders!

- Assume one dimension much larger than $\delta - 1$, which are much larger than M_F^{-1}

- Sterile neutrinos $N_{L,R}$ can propagate in bulk with gravitons (other matter confined to brane)

- Lowest N_R are Dirac partners of active ν_L on brane, with volume suppressed Yukawa couplings

$$m_D \sim hvM_F/\bar{M}_{Pl}$$

h is a Yukawa coupling, v is electroweak scale. For $h \sim 1$ and $M_F \sim$ 100 TeV, $m_D \sim 10^{-2}$ eV

- No light on mixings
- Kaluza Klein (KK) towers of sterile neutrino excitations (lepton number conserving in simplest scheme)
- Original: use oscillations into tower for Solar/atmospheric. Now: leakage into sterile as perturbation
- Minimal scheme: small Dirac masses and KK (kinetic) masses: no LSND enhancement (cancellations between towers)
- Can add additional effects, e. g. extra Majorana masses

Upper bounds on R (cm) at 90% c.l. and the corresponding lower bounds on $1/R$ (eV)

Experimental Bounds			
Experiment	Hierarchical (cm, eV)	Inverted (cm, eV)	Degenerate (cm, eV)
CHOOZ	$(9.9 \times 10^{-4}, 0.02)$	$(3.3 \times 10^{-5}, 0.60)$	$(1.8 \times 10^{-6}, 10.9)$
BUGEY	none	$(4.3 \times 10^{-5}, 0.46)$	$(2.4 \times 10^{-6}, 8.3)$
CDHS	none	none	$(5 \times 10^{-6}, 4)$
Atmospheric	$(8.2 \times 10^{-5}, 0.24)$	$(6.2 \times 10^{-5}, 0.32)$	$(4.8 \times 10^{-6}, 4.1)$
Solar	$(1.0 \times 10^{-3}, 0.02)$	$(8.9 \times 10^{-5}, 0.22)$	$(4.9 \times 10^{-6}, 4.1)$

Mixing with heavy neutrinos (including nonorthogonal)

- Mixing of ordinary neutrinos with heavy ($M > M_Z/2$) neutrinos
  - Need enhanced mixings
  - Active? (Fourth family disfavored by precision)

- Reduced couplings: can account for NuTeV, but affects G_F (Problems for M_W, M_Z vs asymmetries, and possibly CKM universality (but V_{us}?))

- Nonorthogonal neutrinos: neutrino mixing matrix for light neutrinos is nonunitary due to mixing with heavy

$$\sum_{i=1}^{3} V_{ei}^* V_{\mu i} = -\sum_{i=4}^{N} V_{ei}^* V_{\mu i} \neq 0$$

- **In** $\mu^+ \rightarrow \bar{\nu}_\mu^{\rm light} e^+ \nu_e^{\rm light}$, **where** $\bar{\nu}_\mu^{\rm light} \equiv \sum_{i=1}^3 V_{\mu i} \bar{\nu}_i$, $\bar{\nu}_\mu^{\rm light}$ **can rescatter to produce** e^+ **(independent of** L/E**)**

- **However, NOMAD** $\nu_\mu \rightarrow \nu_e$ **limits make too small for LSND**

- **May be small CP violating effects in SBL expriments**

Magnetic moments (SP, RSFP, RSFP + oscillations)

- Dirac: direct and transition
- Majorana: transition only
- Lab limits: $|\mu_\nu| \lesssim 10^{-10} \mu_B$
- Astrophysical limits: $|\mu_\nu| \lesssim \mathrm{few} \times 10^{-12} \mu_B$
- Theory: expect $\mu_\nu \sim 10^{-19} \mu_B (m_\nu / 1$ eV) unless symmetry decouples m_ν, μ_ν

- Solar: first motivated by Sunspot correlations, but can still be present (now subleading) for fields deeper in Sun (depends on poorly known Solar field)

- Spin precession (SP) in Sun (Dirac): $\nu_{eL} \rightarrow \nu_{eR}$

- Resonant spin flavor precession (RSFP) in Sun $\nu_{eL} \rightarrow \nu^c_{\mu R}$

- RSFP + oscillations, $\nu_{eL} \rightarrow \nu^c_{eR}$ at possibly observable level

Neutrino decay

- Relevant modes
  - Radiative: $\nu_2 \rightarrow \nu_1 \gamma$ small by limits on transition moments and nonobservation of diffuse relic background, etc.
  - $\nu_2 \rightarrow \nu_1 \nu_1 \bar{\nu}_1$, too slow
  - $\nu_2 \rightarrow \nu_1 X, \quad \bar{\nu}_1 X$, $X =$ Majoran possible

    (Can consider constraints from disappearance or including ν_1)
  - Large scale structure

- Strong constraints on lifetime from Solar spectrum

  (Could obtain $\bar{\nu}_e$)

- Most parameter ranges for atmospheric not viable

- High energy astrophysical neutrinos: can have distortion of canonical $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

  (which follows for initial $1 : 2 : 1$ and maximal $\nu_\mu - \nu_\tau$ mixing)

TABLE I. Flavor ratios for various decay scenarios.

Unstable	Daughters	Branchings	$\phi_{\nu_e}:\phi_{\nu_\mu}:\phi_{\nu_\tau}$
ν_2, ν_3	anything	irrelevant	6:1:1
ν_3	sterile	irrelevant	2:1:1
ν_3	full energy	$B_{3\to 2} = 1$	1.4:1:1
	degraded ($\alpha = 2$)		1.6:1:1
ν_3	full energy	$B_{3\to 1} = 1$	2.8:1:1
	degraded ($\alpha = 2$)		2.4:1:1
ν_3	anything	$B_{3\to 1} = 0.5$	2:1:1
		$B_{3\to 2} = 0.5$	

CPT violation

- **Motivated as alternative explanation for LSND**

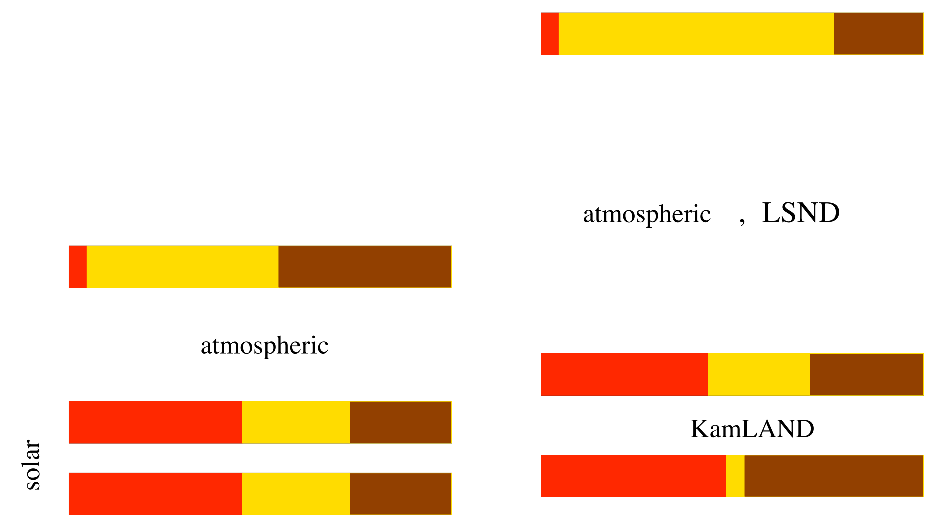
- **Need deviation from local field theory**

  (In principle from strings, LED, background fields)

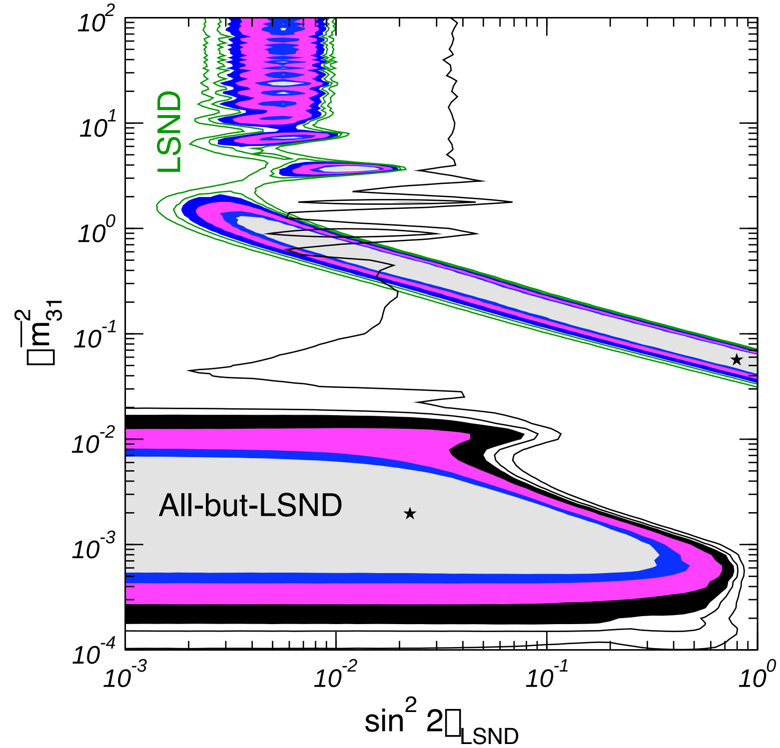
- **Different ν and $\bar{\nu}$ spectra allow 3 mass differences**

- **$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (not $\nu_\mu \rightarrow \nu_e$) for LSND**

- **Lose Solar (excluded by KamLAND) or atmospheric range for $\bar{\nu}$**



- **$2\nu+$ CPT probably excluded**
- **$3\nu+$ CPT probably excluded (and no evidence w/o LSND)**
- **$4\nu + CPT$ fits data**
- **Future: MINOS atmospheric, MiniBooNE**



New interactions

- **Strongly constrained by precision EW**
  (hard to accomodate NuTeV)

- **FCNC in Sun rather than oscillations (original Wolfenstein paper!) now excluded by KamLAND, but could be perturbation**

- **Alternative explanation of LSND: L flavor violating interaction $\mu^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu$ (but rare mu decays), or L violation $\mu^+ \rightarrow e^+ \bar{\nu}_e \bar{\nu}_i$**

- **Would *not* be seen by MiniBooNE (π decay)**

- **Excluded by KARMEN at rate needed for LSND (no distance effect)**

- **Future: TWIST at TRIUMF (μ decay)**

Neutrino-antineutrino oscillations

- Search for wrong sign lepton produced in neutrino scattering ($\pi^+ \to \mu^+ \nu, \quad \nu p \to \mu^+ X$)
- New operators? Stringent limits from decays
- Majorana neutrinos don't conserve L, but need helicity flip
- Can produce wrong helicity in decay or flip in rescattering (e.g., $\pi^+ \to \mu^+ \bar{\nu}_R$), but rate suppressed by $(m_\nu / E_\nu)^2$
- Lepton number violating oscillations can be large in sterile ν schemes (e.g., $\nu_L \to N_L^c$), but resulting state is sterile; must invoke new interaction (e.g. W_R) or more complicated exotic fermion mixings (N_L^c not really sterile)
- Confusion of $\nu_\mu \to \bar{\nu}_\mu$ with $\bar{\nu}_e \to \bar{\nu}_\mu$ in $\mu^- \to e^- \nu_\mu \bar{\nu}_e$

model	parameters	$\frac{\mu^+ events}{\mu^- events}$
Pure Majorana	m_{ν_μ}	$< 10^{-10}$
Spin precession in $B_\perp$	$\lvert\mu_{\nu_\mu}\rvert < 7.4 \times 10^{-10} \mu_B$ $\Delta m^2 \sim 10^{-5}\ eV^2$	$< 2 \times 10^{-6}$ $(L \sim 1\ km)$
Neutrino Decay	$h_2^2 < 0.1$, $m_{\nu_\mu} \sim 10\ eV$, $\sin^2 2\theta_\mu < 0.02$	$< 4 \times 10^{-7}$
$SU(2)_L \times SU(2)_R \times U(1)$	$\lvert\xi_g\rvert < 0.003$, $\beta_g < 0.004$ $\sin^2 2\theta_\mu < 0.02$ for $\Delta m^2 = 100\ eV^2$	$< 3 \times 10^{-7}$ $(L \sim 1\ km)$
Exotic fermions	$\lvert U_{13}^2\rvert < 0.027$, $\theta_{\mu R},\ \theta_{\mu L} \sim 0.0014$	$< 4 \times 10^{-8}$

TABLE I. μ^+, μ^- events ratio of high energy ν_μ ($\sim 1\ GeV$) N scattering for five neutrino-antineutrino oscillation scenarios. (e^+, μ^- events ratio for the spin precession scenario.)

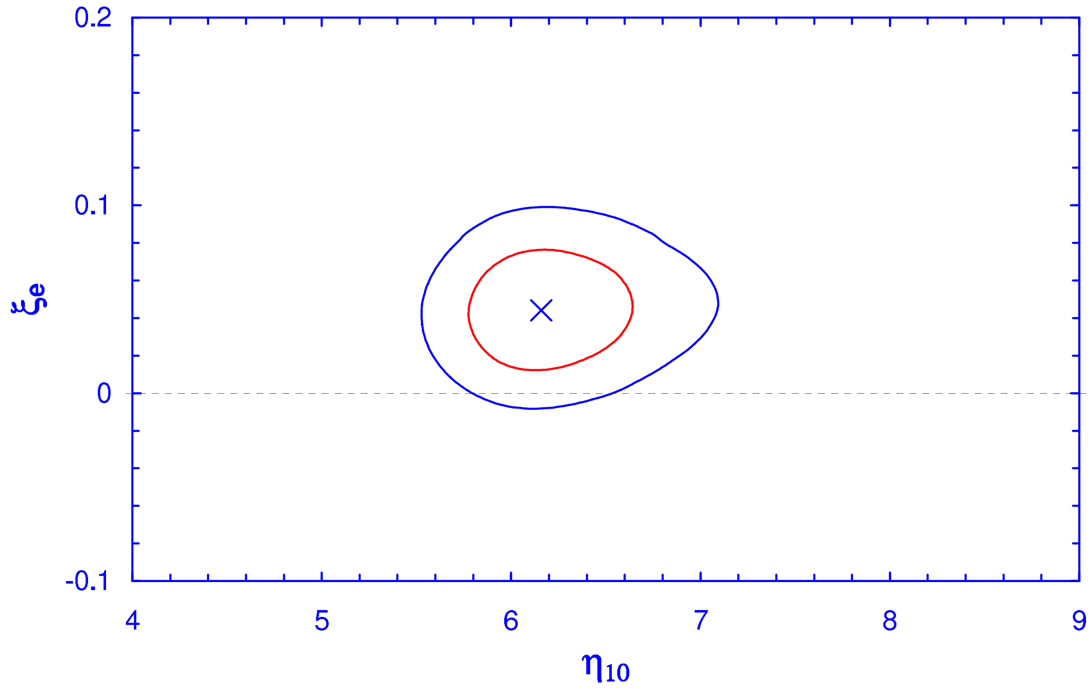
Large neutrino degeneracies

- **Expect $n_\nu - n_{\bar{\nu}} \sim 10^{-10} n_\nu$**

- **However, $O(0.01 - 0.1)$ asymmetry important for BBN**

- **Hint from ^4He abundance**

- **Suppresses or compensates sterile production or ν_R in $U(1)'$**



What if MiniBooNE sees a positive signal?

- No very satisfactory explanation: all suggestions have theoretical, observational, and possibly cosmological difficulties

- All the more interesting if found
  - New interactions: origin?
  - Sterile neutrino: look for L/E dependence. Much richer for oscillation experiments
  - CPT violation: compare ν_μ and $\bar{\nu}_\mu$. Profound consequences; nonlocal physics

Relic neutrinos

- $\nu_i, \bar{\nu}_i$ decoupled at $T_D \sim$ few MeV
- Now at 1.9 K, 50/cm^3 for each d.o.f
- For hierarchical pattern $\langle v_3 \rangle \sim 10^{-2}$, $\langle v_2 \rangle \sim 10^{-1}$
- For degenerate pattern, $\langle v_i \rangle \sim 2 \times 10^{-3} \left(\frac{0.23 \ eV}{m_i} \right)$
- Little clustering unless $m_i \gtrsim 0.3 \ eV$, and then on supercluster scale

- Important for large scale structure and BBN
- Direct detection (scattering, torques, forces) impractical
- Scattering of high energy cosmic ray neutrinos (Z-burst)
  - Account for $E_p >$ GZK?
  - Future observation? Depends on unknown flux of UHE ν

Conclusions

- Nature is probably a standard 3 ν hierarchy
- But be ready for surprises